MAX-PLANCK-GESELLSCHAFT

Max Planck Institute
for Astrophysics

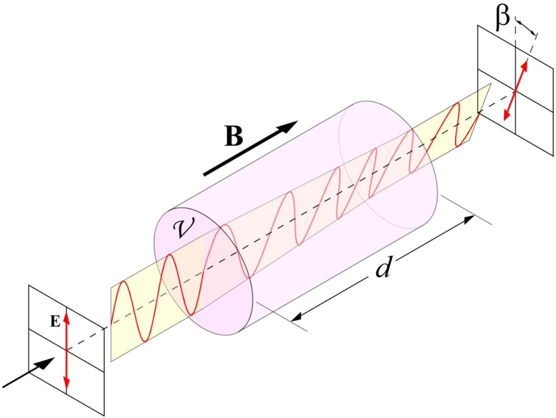
The Galactic Faraday sky
–
What it is, how it's done, and why it's useful

Niels Oppermann

with
G. Robbers, T.A. Enßlin, H. Junklewitz, M.R. Bell, A. Bonafede, R. Braun, J.-A.C. Brown, T.E. Clarke, I.J. Feain, B.M. Gaensler, A. Hammond, L. Harvey-Smith, G. Heald, M. Johnston-Hollitt, U. Klein, P.P. Kronberg, S.A. Mao, N.M. McClure-Griffiths, S.P. O'Sullivan, L. Pratley, T. Robishaw, S. Roy, D.H.F.M. Schnitzeler, C. Sotomayor-Beltran, J. Stevens, J.M. Stil, C. Sunstrum, A. Tanna, A.R. Taylor, and C.L. Van Eck

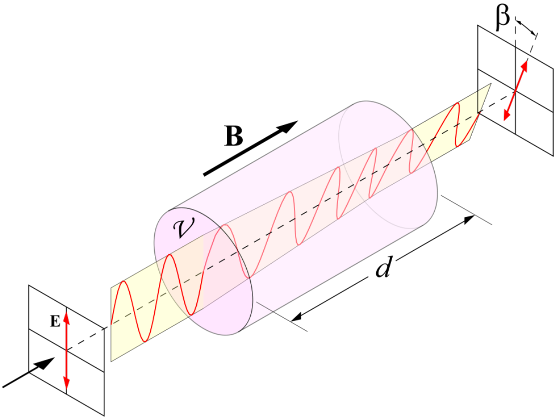
DFG research group 1254 annual meeting, Mainz, 2012-07-09

What it is



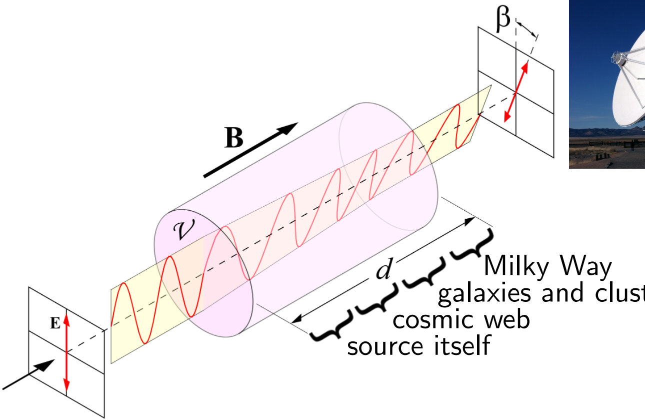
$$\mathrm{d}\beta \propto \lambda^2 n_\mathrm{e}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$

$$\Rightarrow \quad \beta \propto \lambda^2 \int_{r_\mathrm{source}}^{0} n_\mathrm{e}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$



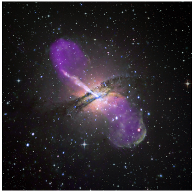
Faraday depth: $\phi \propto \int_{r_{\mathrm{source}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$

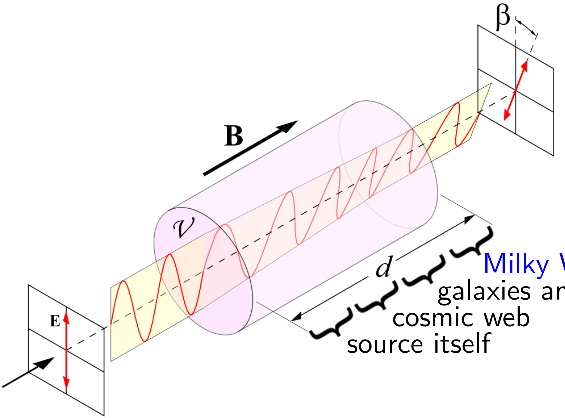
$$\beta = \phi\lambda^2$$

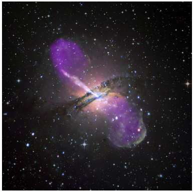


Faraday depth: $\phi \propto \int_{r_{\mathrm{source}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$

$$\beta = \phi \lambda^2$$

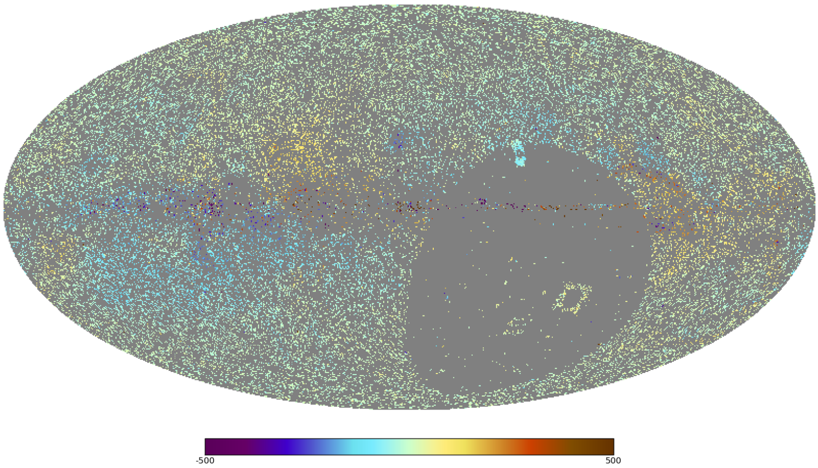




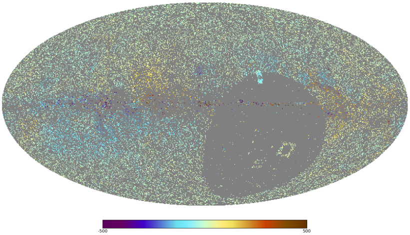


Galactic Faraday depth:

$$\phi \propto \int_{r_{\mathrm{MilkyWay}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$



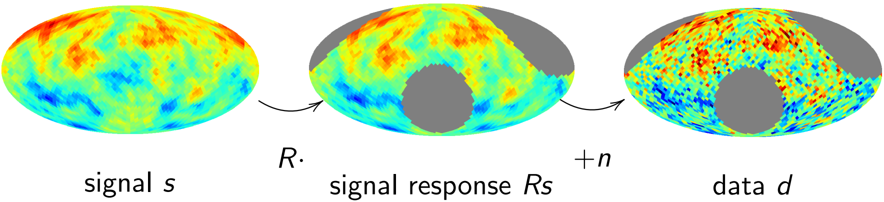
41 330 data points



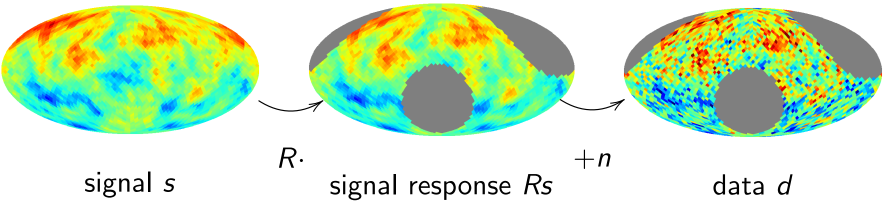
Challenges

- Regions without data
- Uncertain error bars:
  - complicated observations
  - $n\pi$-ambiguity
  - extragalactic contributions unknown

How it's done



$$\boxed{d = Rs + n}$$

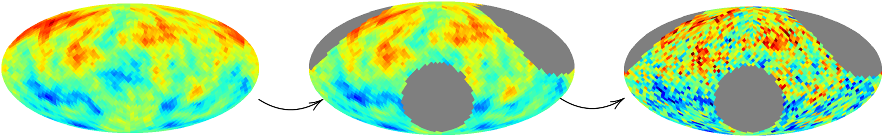


$$\boxed{d = Rs + n}$$

$$\mathcal{P}(s) = \mathcal{G}(s, S)$$

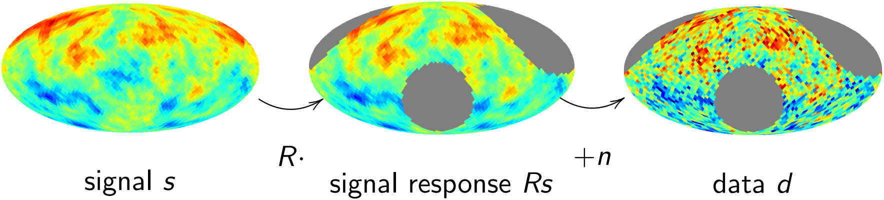
$$\mathcal{P}(n) = \mathcal{G}(n, N)$$

$$\mathcal{G}(s, S) = \frac{1}{|2\pi S|^{1/2}} \exp\left[\frac{1}{2} s^{\dagger} S^{-1} s\right]$$



$$d = Rs + n$$

$$m = \int \mathcal{D}s \; s \; \mathcal{P}(s|d)$$



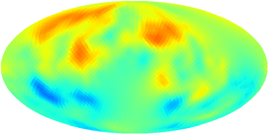
Wiener Filter

$$d = Rs + n$$

$$m = \int \mathcal{D}s \; s \; \mathcal{P}(s|d)$$

$$m = Dj, \;\text{where}\quad \begin{aligned} j &= R^\dagger N^{-1} d \\ D &= \left(S^{-1} + R^\dagger N^{-1} R\right)^{-1} \end{aligned}$$

$\downarrow \; DR^\dagger N^{-1}\cdot$

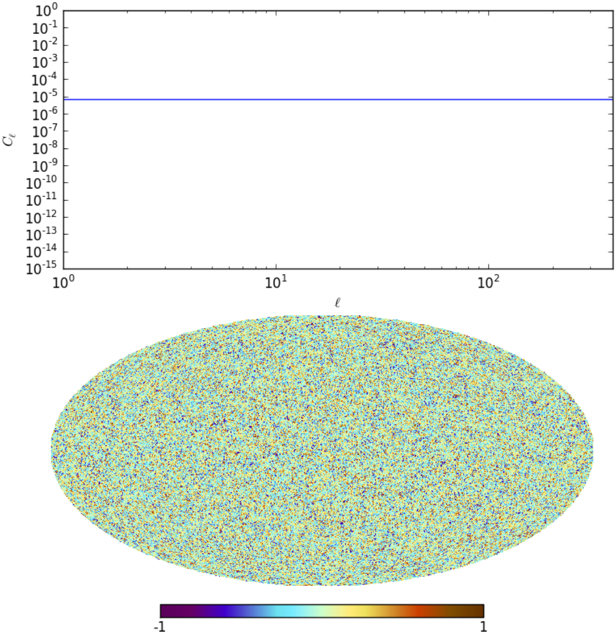


$$S(\hat{n}, \hat{n}') = \int \mathcal{D}s \; s(\hat{n}) s(\hat{n}') \mathcal{P}(s)$$

$$\Rightarrow S_{(\ell m),(\ell' m')} = \int \mathcal{D}s \; s_{\ell m} s^*_{\ell' m'} \mathcal{P}(s)$$

$$
\begin{aligned}
S(\hat{n}, \hat{n}') &= \int \mathcal{D}s \; s(\hat{n}) s(\hat{n}') \mathcal{P}(s) \\
&= S(\hat{n} \cdot \hat{n}') \\
\Rightarrow S_{(\ell m),(\ell' m')} &= \int \mathcal{D}s \; s_{\ell m} s^*_{\ell' m'} \mathcal{P}(s) \\
&= \delta_{\ell \ell'} \delta_{m m'} C_\ell
\end{aligned}
$$

$\hookrightarrow$ angular power spectrum



10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
C_ℓ
10^{0}
10^{1}
10^{2}
ℓ
-1
1

$$
\begin{aligned}
S(\hat{n}, \hat{n}') &= \int \mathcal{D}s \; s(\hat{n}) s(\hat{n}') \mathcal{P}(s) \\
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&= \delta_{\ell \ell'} \delta_{m m'} C_\ell
\end{aligned}
$$

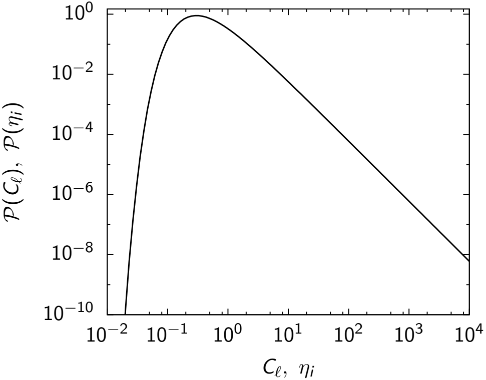
$\hookrightarrow$ angular power spectrum

$$
N_{ij} = \delta_{ij} \sigma_i^2
$$

(uncorrelated noise)

$$S_{(\ell m),(\ell' m')} = \delta_{\ell\ell'}\delta_{mm'} C_\ell \qquad N_{ij} = \delta_{ij}\eta_i\sigma_i^2$$

$$S_{(\ell m),(\ell' m')} = \delta_{\ell\ell'}\delta_{mm'} C_\ell \qquad N_{ij} = \delta_{ij}\eta_i\sigma_i^2$$



$\Rightarrow$ marginalize over all possible parameters

Problem: $\mathcal{P}(s|d)$ is non-Gaussian.
Solution: Find Gaussian $\mathcal{G}(s - m, D)$, that best approximates $\mathcal{P}(s|d)$.

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Solution: Find Gaussian $\mathcal{G}(s-m, D)$, that best approximates $\mathcal{P}(s|d)$.

Extended Critical Filter

$$m = Dj, \quad D = \left[\sum_\ell C_\ell^{-1} S_\ell^{-1} + \sum_i \eta_i^{-1} R^\dagger N_i^{-1} R\right]^{-1},$$

$$j = \sum_i \eta_i^{-1} R^\dagger N_i^{-1} d$$

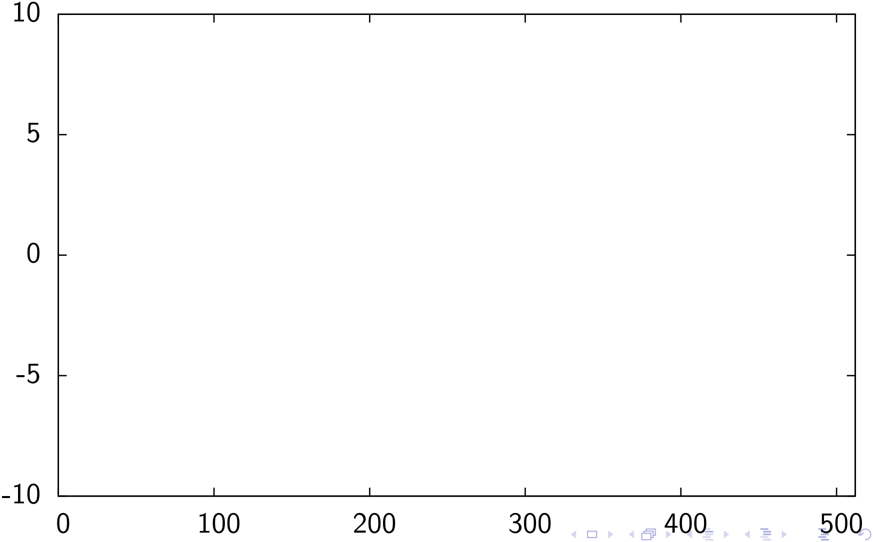
$$C_\ell = \frac{1}{\alpha_\ell + \ell - 1/2}\left[q_\ell + \frac{1}{2}\mathrm{tr}\left(\left(mm^\dagger + D\right) S_\ell^{-1}\right)\right]$$

$$\eta_i = \frac{1}{\alpha_i}\left[q_i + \frac{1}{2}\mathrm{tr}\left(\left((d-Rm)(d-Rm)^\dagger + RDR^\dagger\right) N_i^{-1}\right)\right]$$

1D test case

Assumptions:

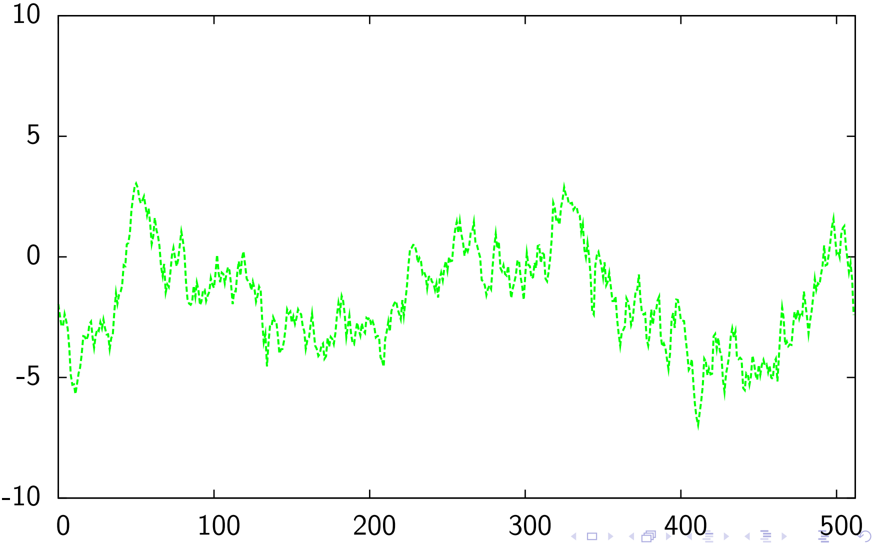
-
-



1D test case

Assumptions:

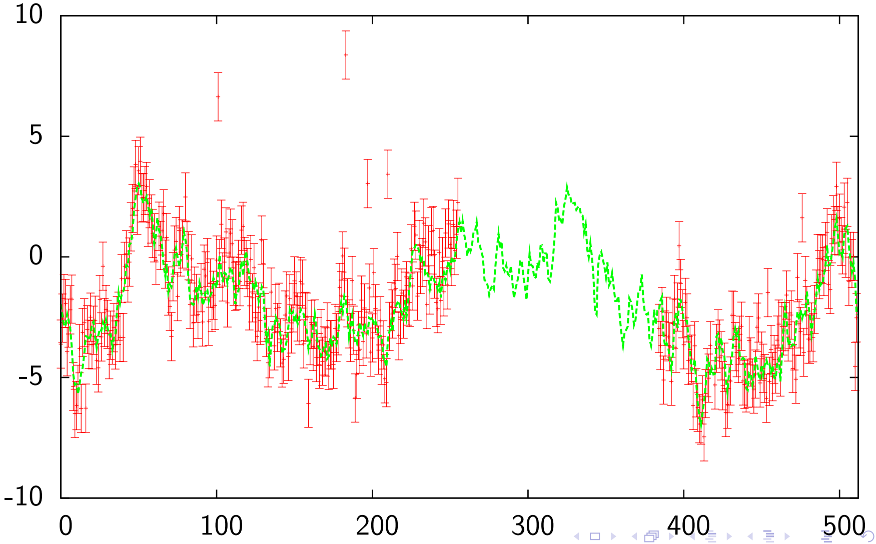
- signal field statistically homogeneous Gaussian random field
-



1D test case

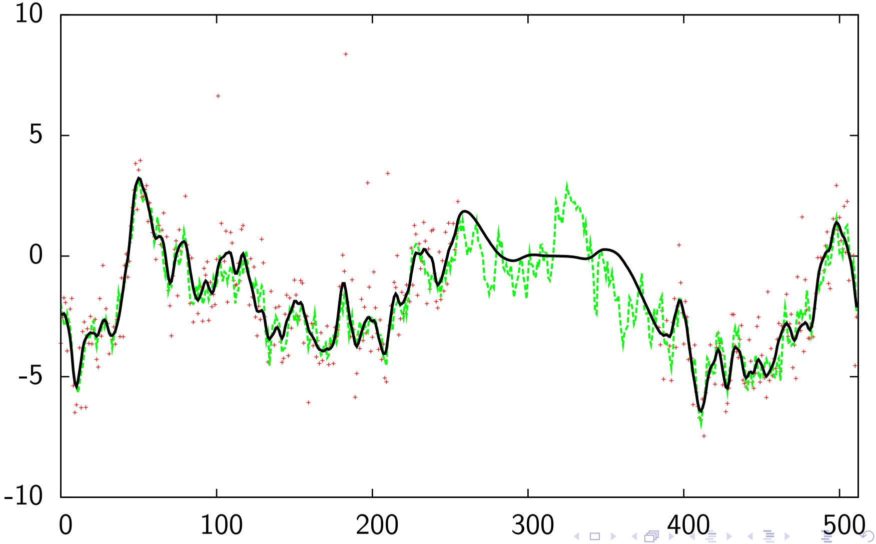
Assumptions:

- signal field statistically homogeneous Gaussian random field
- noise uncorrelated, Gaussian



1D test case

- Reconstruct (iteratively):
  signal, power spectrum, noise variance



1D test case

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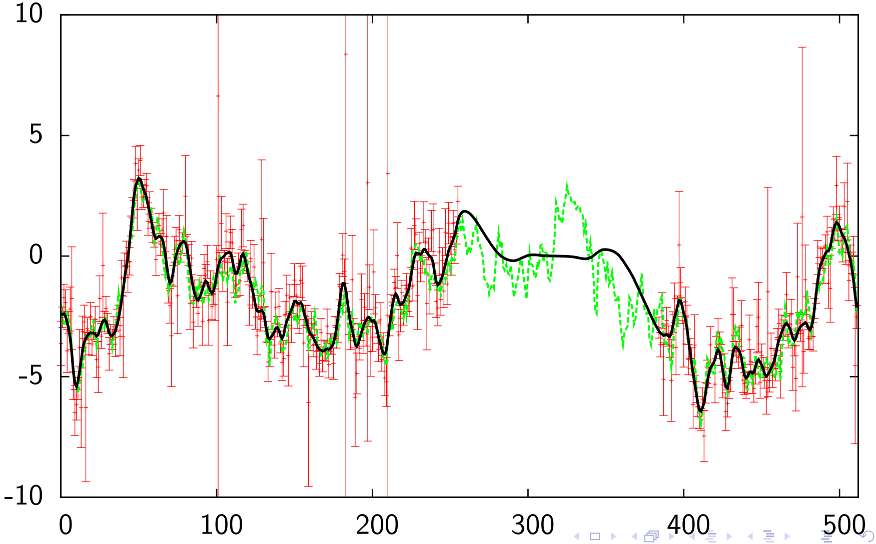
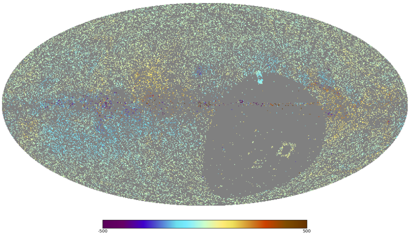
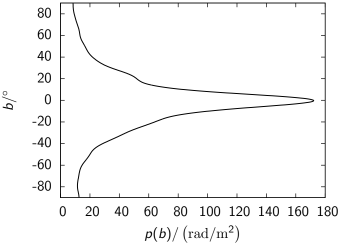
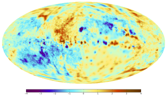
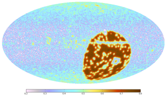
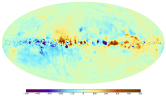
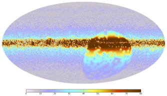
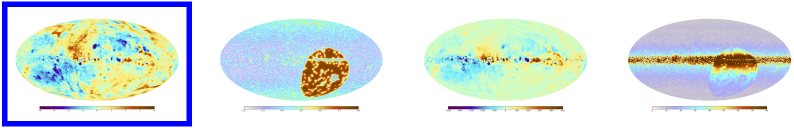




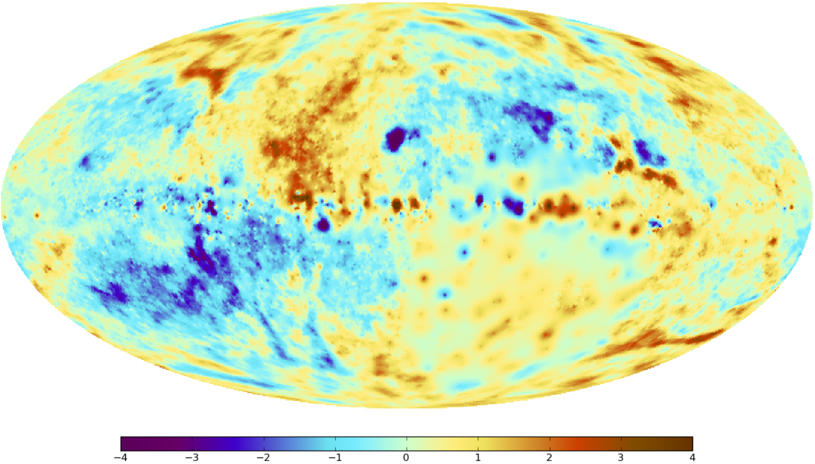


- Approximate $s(b,l) := \frac{\phi(b,l)}{p(b)}$ as a statistically isotropic Gaussian field
- R: multiplication with $p(b)$ and projection on directions of sources
- $N_{ij} = \delta_{ij}\eta_i\sigma_i^2$

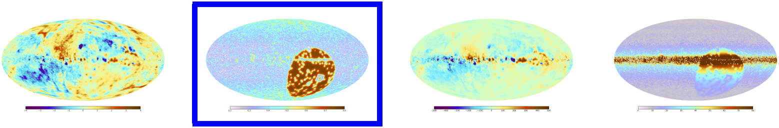







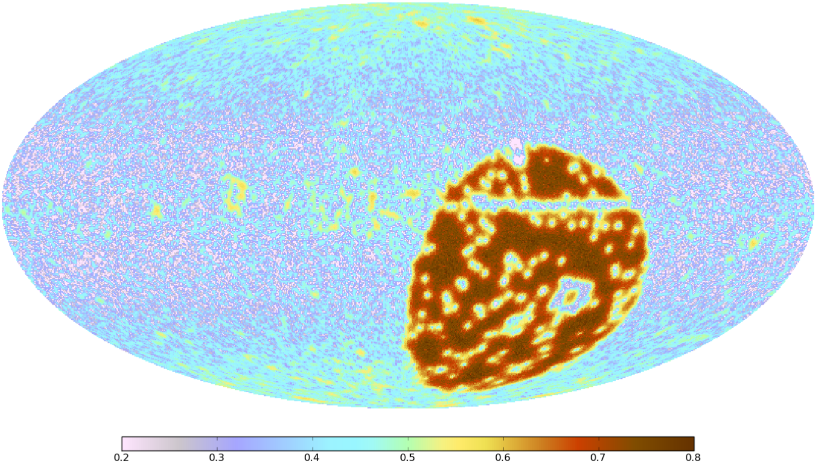
posterior mean of the signal



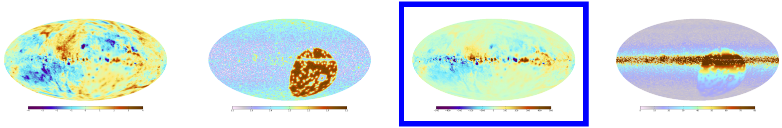
m



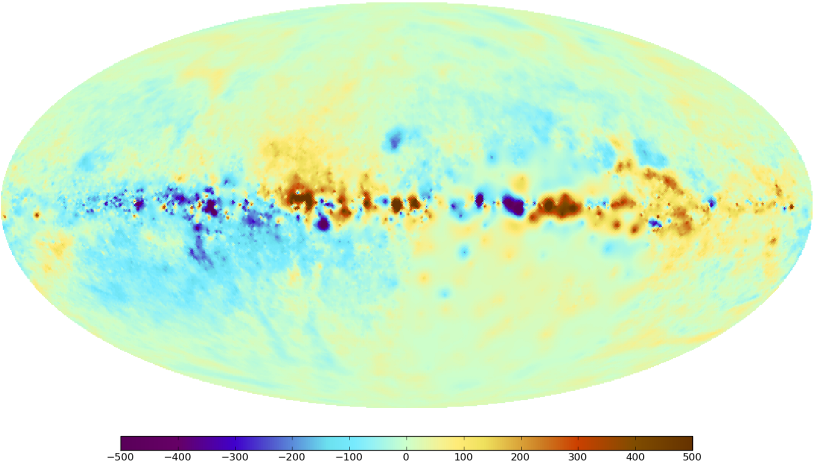
uncertainty of the signal map



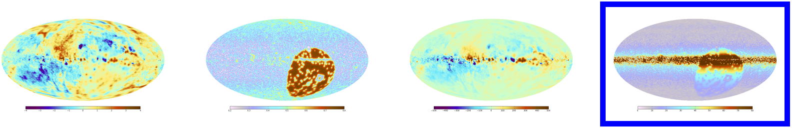
$$\sqrt{\operatorname{diag}(D)}$$



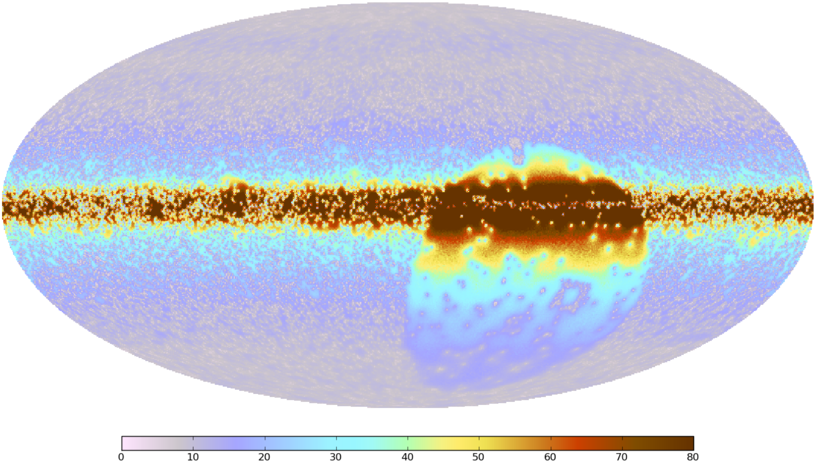
posterior mean of the Faraday depth



pm

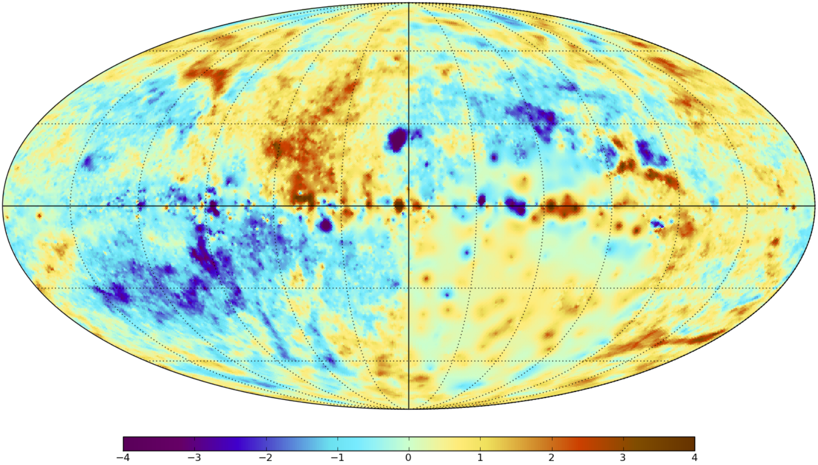


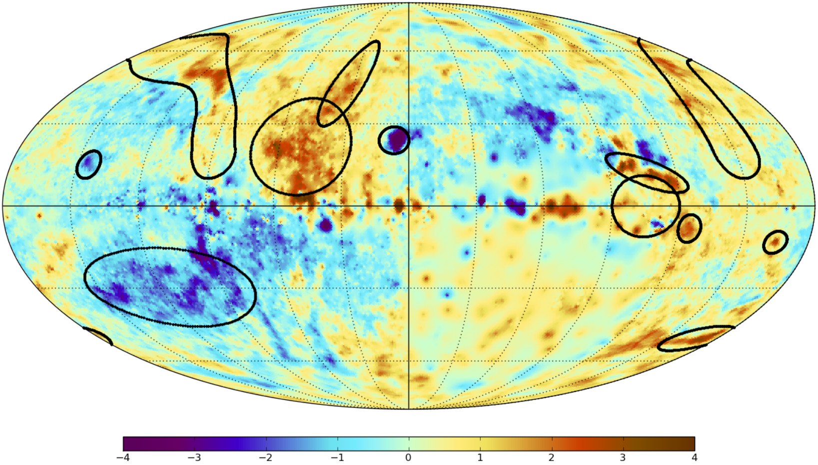
uncertainty of the Faraday depth



$$p\sqrt{\mathrm{diag}\,(D)}$$

Why it's useful


−4
−3
−2
−1
0
1
2
3
4


−4
−3
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0
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3
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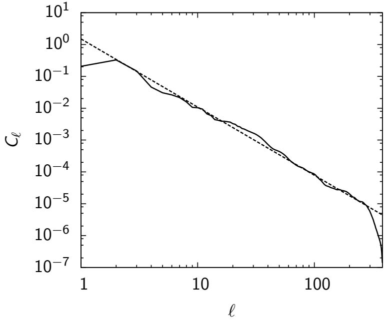
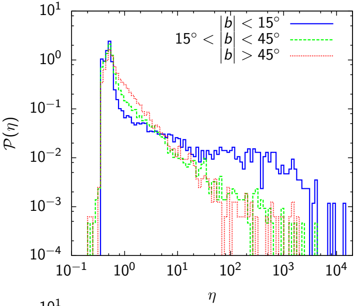
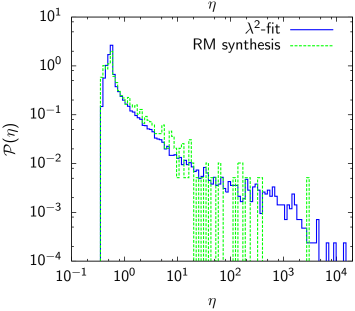
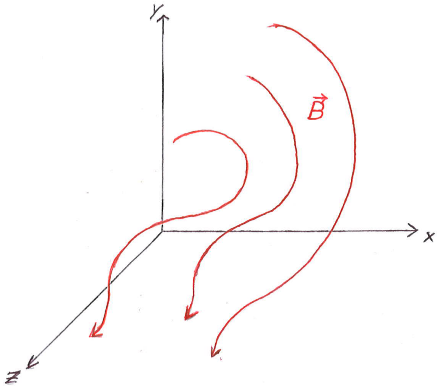


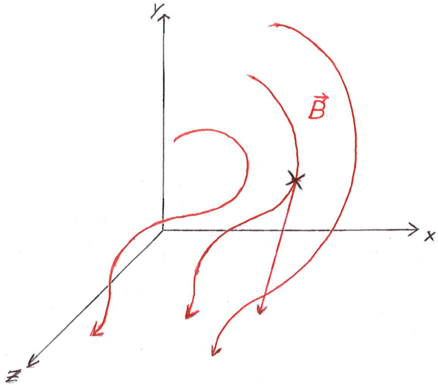
$$C_\ell \propto \ell^{-2.17}$$



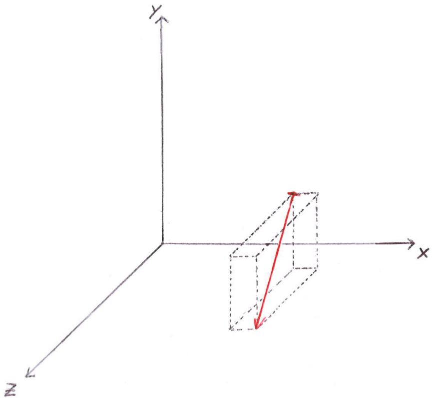


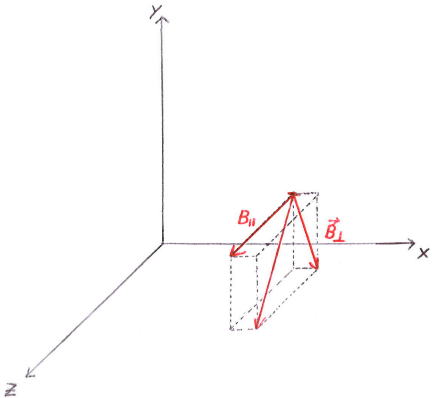
$$N_{ij} = \langle n_i n_j \rangle = \delta_{ij} \eta_i \sigma_i^2$$


y
x
z
$\vec{B}$

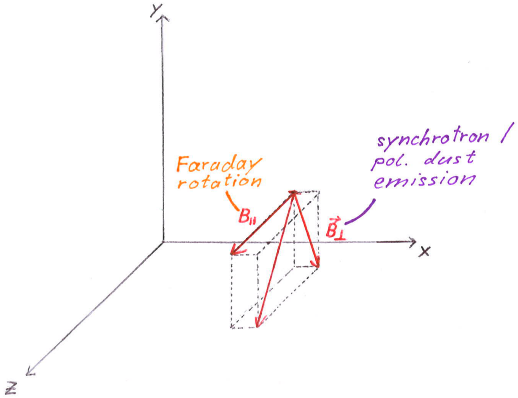


y
$\vec{B}$
x
z

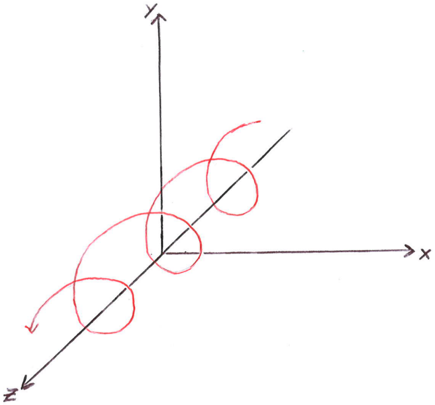

Y
X
Z

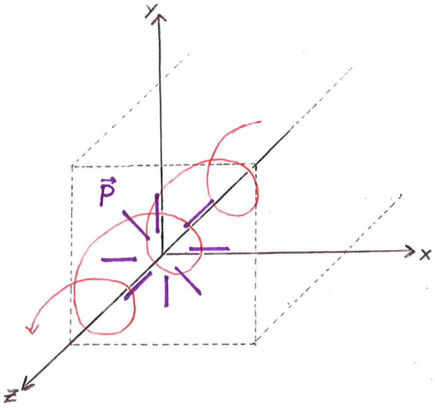


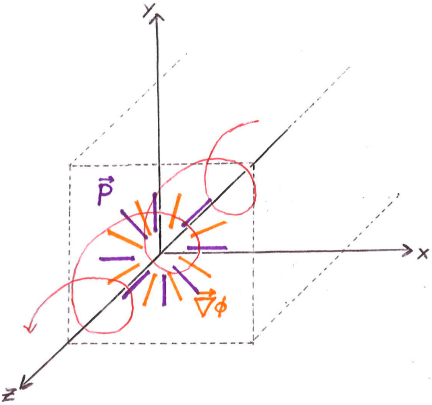
Y
X
Z
$B_{\parallel}$
$\vec{B}_{\perp}$



Y
X
Z
Faraday rotation
$B_{\parallel}$
$\vec{B}_{\perp}$
synchrotron / pol. dust emission

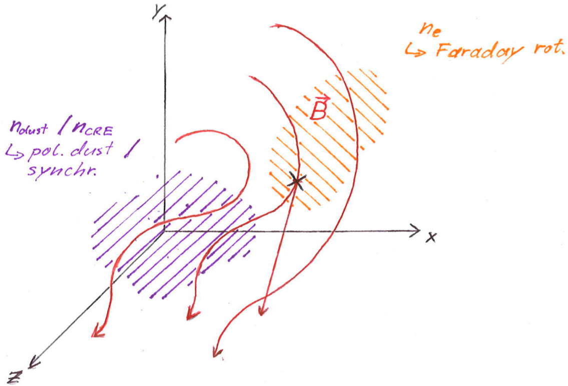

y
x
z


y
x
z
$\vec{P}$



known as **LITMUS** procedure

Junklewitz et al. 2011A&A...530A..88J
Oppermann et al. 2011A&A...530A..89O


y
x
z
n_{dust} / n_{CRE}
↳ pol. dust / synchr.
n_e
↳ Faraday rot.
$\vec{B}$

www.icr.org/article/what-causes-galaxys-magnetism/

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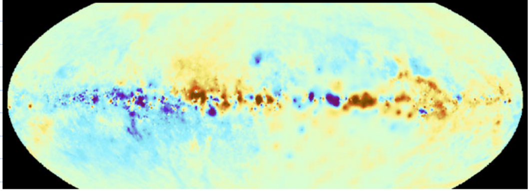

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What Causes a Galaxy's Magnetism?

Send This

by Brian Thomas, M.S. *

Secular astronomers are no closer to understanding what could cause galactic magnetic fields than they were when they first detected the fields over a century ago. And although the most recent map of the Milky Way's magnetic field shows unprecedented detail, it gives no clues to the question of magnetic field formation through natural forces. Did this field require a Creator for its origin?

An international team of radio astronomers compiled over 41,000 radio signals that had travelled through the Milky Way galaxy from distant stars to earth. The team applied an algorithm to the stellar data to help resolve the degree of twisting—called the Faraday effect—that the Milky Way induced on the radio light. The researchers inferred and mapped

Summary

- New map of the Galactic contribution to Faraday depth
- Extragalactic contributions filtered out via spatial correlation structure
- Potential for studies of
  - Interstellar medium
  - Galactic magnetic field
  - Extragalactic sources

All results available at
http://www.mpa-garching.mpg.de/ift/faraday/